

# UK Patent Application (19) GB (11) 2 293 652 (13) A

(43) Date of A Publication 03.04.1996

(21) Application No 9516618.7

(22) Date of Filing 14.08.1995

(30) Priority Data

(31) 08298718

(32) 31.08.1994

(33) US

(51) INT CL<sup>6</sup>  
G01V 1/48

(52) UK CL (Edition O )  
G1G GMB

(56) Documents Cited  
GB 2268021 A

(58) Field of Search  
UK CL (Edition N ) G1G GEL GMB  
INT CL<sup>6</sup> G01V 1/00 1/48 1/50

(71) Applicant(s)

Schlumberger Limited

(Incorporated in the Netherlands Antilles)

277 Park Avenue, New York, NY 10172,  
United States of America

(72) Inventor(s)

Kenneth W Winkler

(74) Agent and/or Address for Service

B D Stoole  
Schlumberger plc, 1st Floor 1 Kingsway, LONDON,  
WC2B 6XH, United Kingdom

## (54) Predicting mechanical failure in underground formations

(57) A method for determining whether a formation is subject to incipient failure is disclosed. The method comprises determining in situ a nonlinear parameter of a formation, and determining whether the nonlinear parameter and/or a derivative of that nonlinear parameter as a function of stress has a relatively large negative value in order to determine whether the formation is subject to incipient failure. In a preferred embodiment, the nonlinear parameter of the formation is a derivative of the square of the shear or compressional velocity with respect to formation stress. The nonlinear parameter of the derivative of the square of the shear velocity with respect to stress is considered to have a large negative value when it is  $S -0.1 \text{ (km/sec)}^2/\text{MPa}$ , while the nonlinear parameter of the derivative of the square of the compressional velocity with respect to stress is considered to have a large negative value when it is  $S -0.2 \text{ (km/sec)}^2/\text{MPa}$ . The derivative of the square of the shear or compressional velocity with respect to stress is considered to have a large negative value when the derivative is  $S -0.06 \text{ (km/sec)}^2/(\text{MPa})^2$ . Typically, rocks will fail if uniaxially stressed between 1 - 5 MPa beyond any of those points.

GB 2 293 652 A

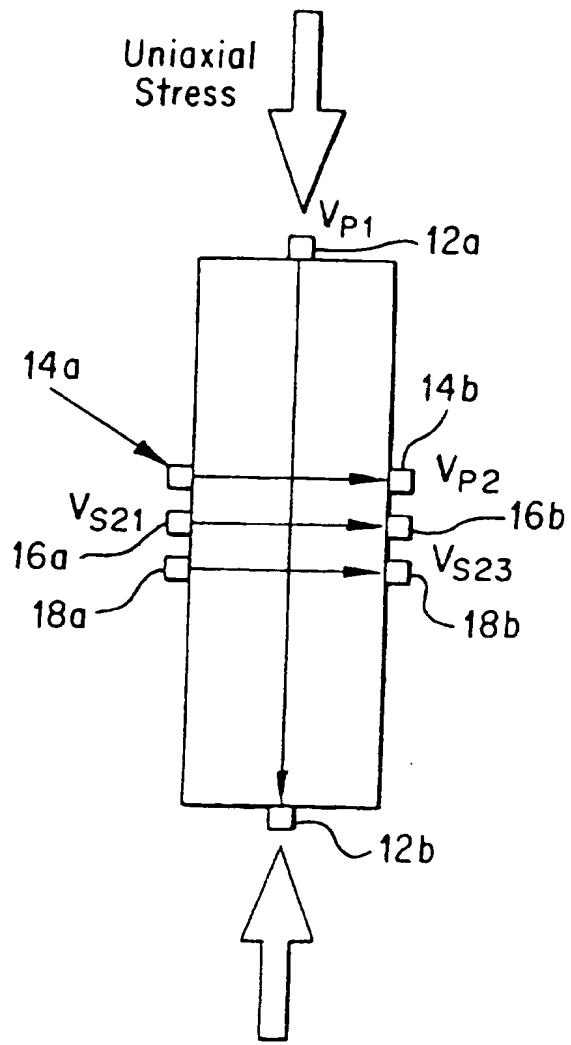


FIG. 1

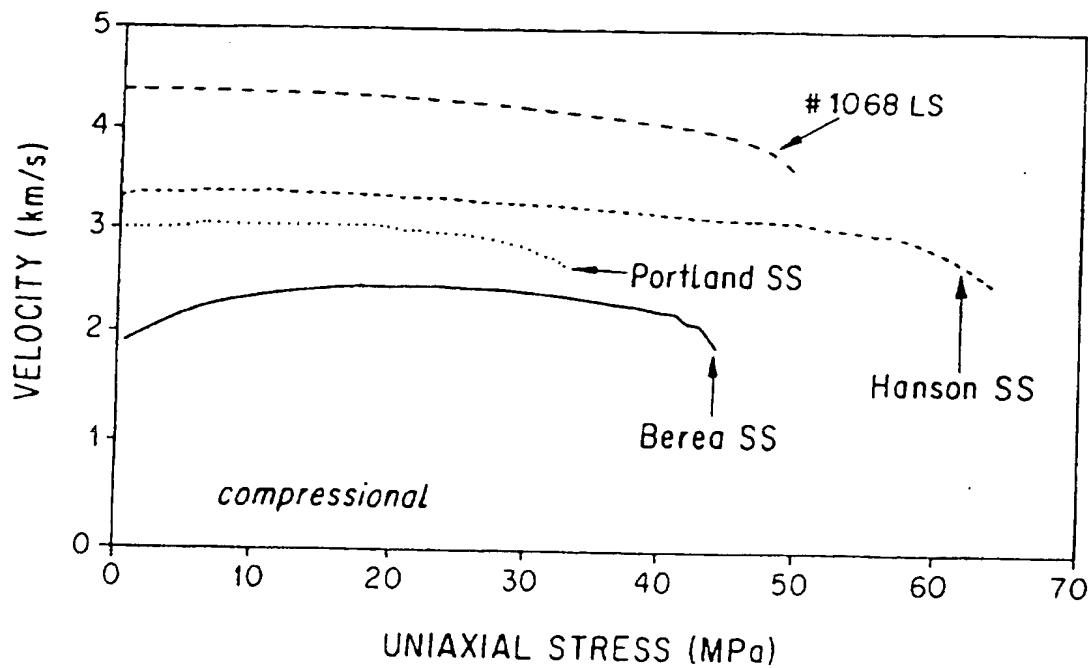


FIG. 2

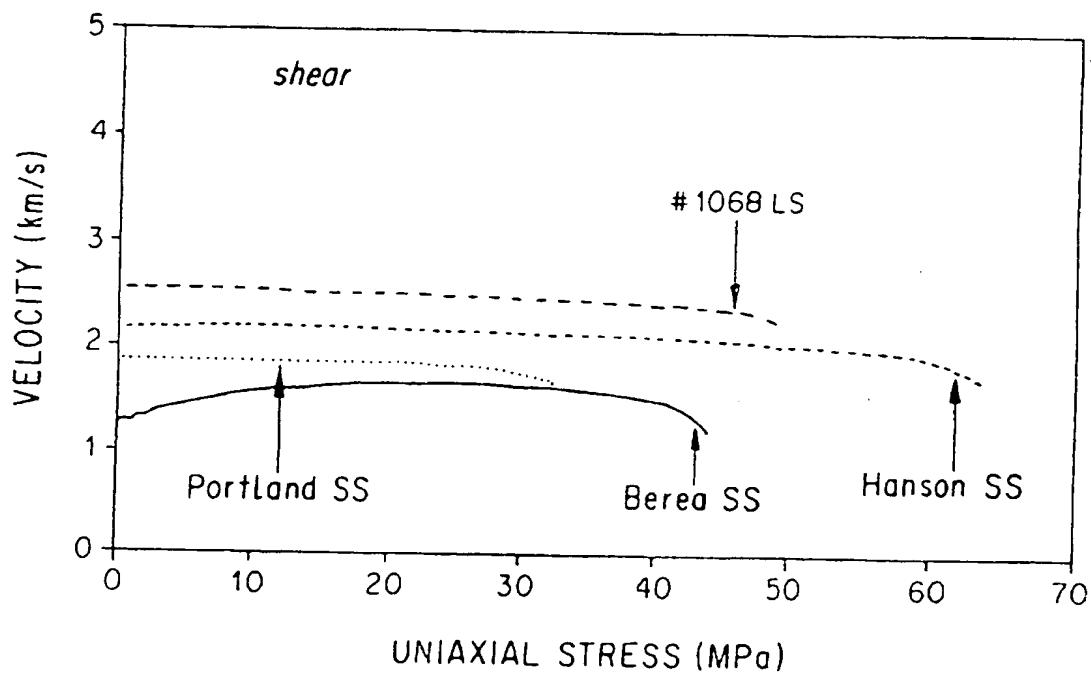


FIG. 3

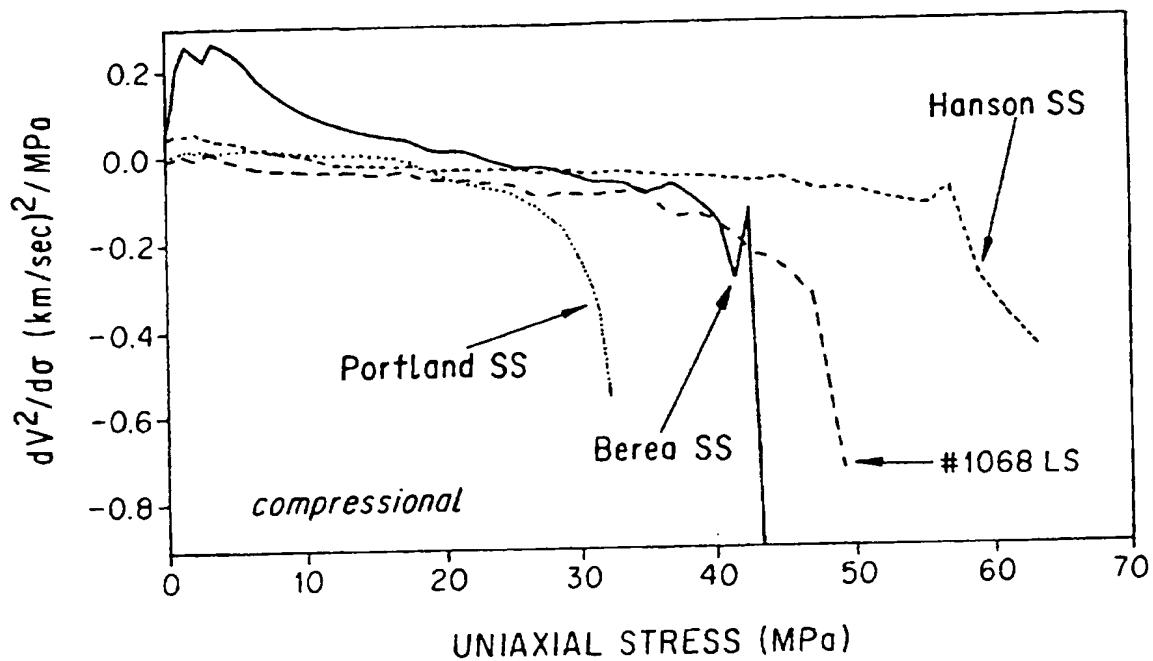


FIG. 4

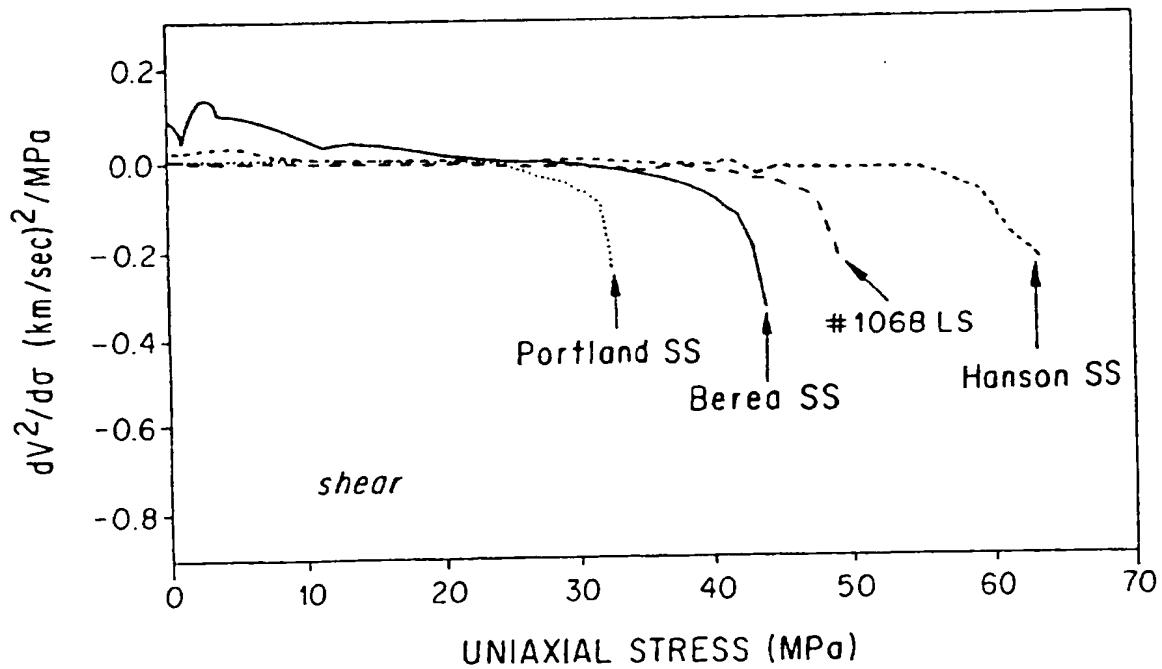


FIG. 5

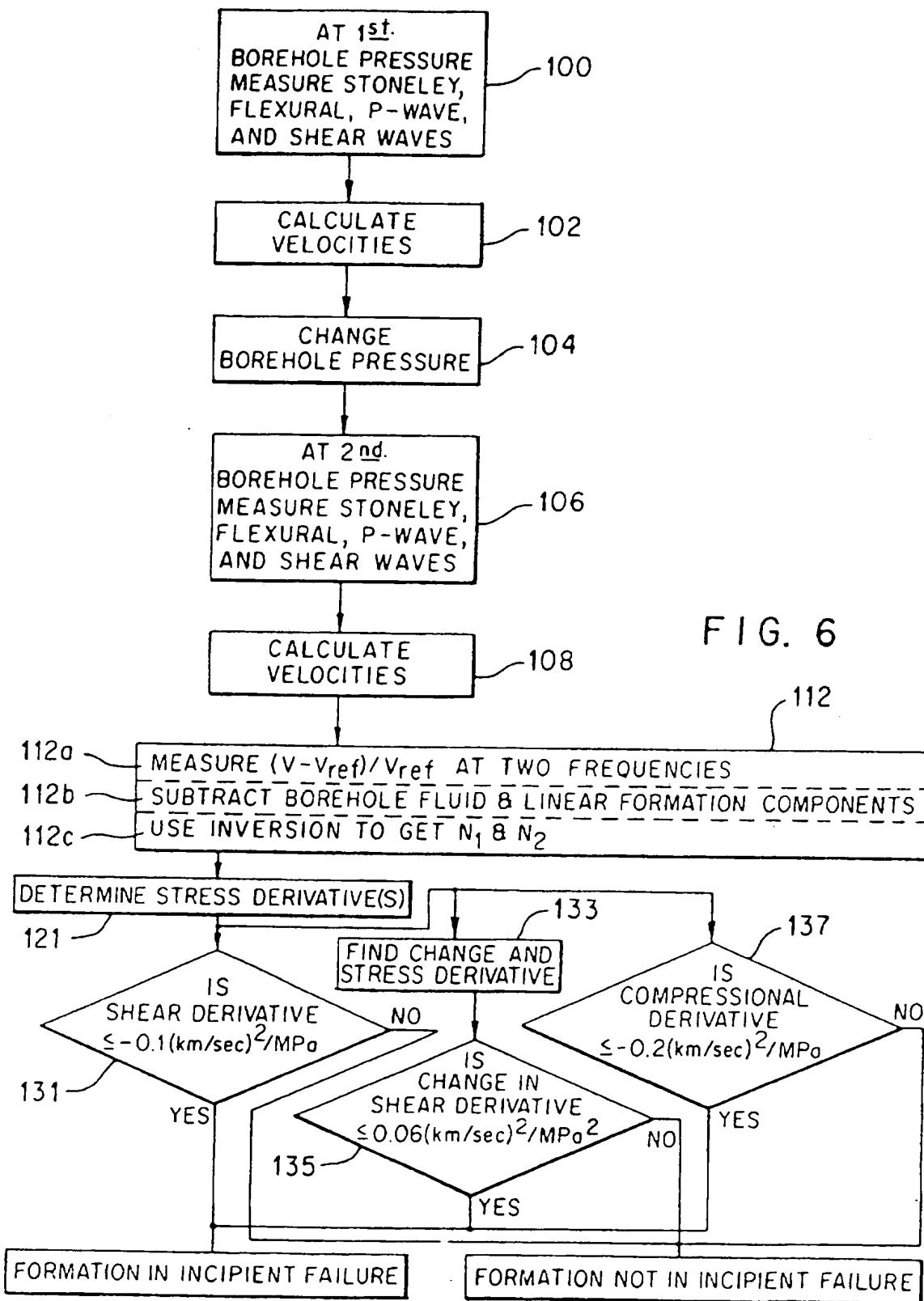


FIG. 6

2293652

**METHODS OF PREDICTING MECHANICAL FAILURE  
IN UNDERGROUND FORMATIONS**

This invention relates broadly to methods for investigating subsurface earth formations. More particularly, the invention provides methods of utilizing determinations of acoustic nonlinear formation parameters in order to determine whether a formation is in danger of collapse.

The art of sonic well logging for use in determining formation parameters is a well established art. Sonic well logs are typically derived from sonic tools suspended in a mud-filled borehole by a cable. The tools typically include a sonic source (transmitter) and a plurality of receivers which are spaced apart by several inches or feet. Typically, a sonic signal is transmitted from the transmitter at one longitudinal end of the tool and received by the receivers at the other, and measurements are made every few inches as the tool is drawn up the borehole. Depending upon the type of transmitter or source utilized (e.g., dipole, monopole), the sonic signal generated by the transmitter travels up the borehole and/or enters the formation adjacent the borehole, and the arrival times of one or more of the compressional (P-wave), shear (S-wave), Stoneley (tube wave), and flexural wave can be detected by the receivers. The receiver responses are typically processed in order to provide a time to depth conversion capability for seismic studies as well as for providing the determinations of formations parameters such as porosity.

While measurements of the compressional and shear waves are useful in quantifying and characterizing various parameters of the formation, it will be appreciated that to date, there has been no successful mechanism for making in situ determinations of nonlinear aspects of the formation; neither has there been a mechanism for interpreting measurements of nonlinear aspects of the formation. For purposes of this invention, it should be understood that the term "nonlinear" when used to describe a material relates to the fact that a plot of stress versus strain in a material will exhibit some nonlinear behavior. In particular, the strain energy function  $U(\varepsilon)$  of an isotropic elastic solid can be written as:

$$U(\varepsilon) = f(\lambda, \mu)\varepsilon^2 + g(\alpha, \beta, \gamma)\varepsilon^3 \quad (1)$$

where  $\varepsilon$  is the strain,  $\lambda$  and  $\mu$  are the second order elastic Lamé constants, and  $\alpha$ ,  $\beta$ , and  $\gamma$  are the third order elastic constants. From equation (1), it will be appreciated that the stress  $\sigma$  is defined by:

$$\sigma = \partial U / \partial \varepsilon = f(\lambda, \mu)\varepsilon + g(\alpha, \beta, \gamma)\varepsilon^2 \quad (2)$$

Based on equation (2) it is seen that the second order Lamé constants are linear constants, while the third order constants are nonlinear, and hence measure the nonlinearity of the material. The more nonlinear the stress versus strain plot is, the more nonlinear the material is said to be. Various manifestations of non-linearity include: the varying of the acoustic velocity in the material when the confining pressure changes; the varying of the acoustic velocity in the material when the amplitude of the acoustic wave changes; the interaction of two monochromatic acoustic beams having different frequencies to create third and fourth acoustic beams having the difference frequency and the additive frequency of the two incident beams; and evidence of frequencies being generated within the material which were not part of any input signal.

In the oil production industry, rock properties such as sanding, fracturing and borehole collapse can be considered to relate to the nonlinear properties of the formation. In each case, the strain in the rock catastrophically exceeds that which would be expected from a linear stress-strain relationship. Since the less consolidated a formation is, the more nonlinear it is, a measurement of the nonlinearity of the formation can provide a measurement of the relative state of the consolidation of the formation. As suggested above, whether a layer of a formation is well or poorly consolidated, can broadly affect the producibility of the layer and formation, as well as the manner in which production is to be carried out.

It is an object of the invention to determine through in situ measurements when a formation is nearing collapse.

This is achieved in accordance with one aspect of the invention by measuring in situ nonlinear parameters of a formation and relating the nonlinear parameters to formation failure.

Another aspect of the invention provides a nonlinear formation parameter which is a direct indicator of formation collapse.

Typically, the method of the invention broadly comprises determining in situ a nonlinear parameter of a formation, and determining whether the nonlinear parameter and/or the slope of a curve of that nonlinear parameter as a function of stress has a

relatively large negative value in order to determine whether the formation is subject to incipient failure. In a preferred embodiment, the nonlinear parameter of the formation is either a derivative of the square of the shear velocity with respect to formation stress, or a derivative of the square of the compressional velocity with respect to stress.

In a preferred method of determining the nonlinear parameter of the formation, velocity measurements of Stoneley and/or flexural waves, and shear and compressional waves are taken at two different pressures in the borehole, and the measurements are used in order to find values for the nonlinear parameters  $N_1$  and  $N_2$  which are related to the desired nonlinear parameter according to equations set forth in that related application. Alternatively, it is possible to take velocity measurements of only the shear and/or compressional waves at two different pressures in the borehole (the pressure relating to stress) and to deconvolve the effect the radial and hoop stress components on the change in velocity measurement.

According to other aspects of the invention, the slope of other indications of nonlinearity in the formation with respect to a change in stress can be used to provide an indication of incipient failure. Such indications of nonlinearity include: the amplitude of a second harmonic tube wave generated in the borehole; the amplitude of an acoustic signal generated in the formation which has a frequency equal to the difference between two acoustic source signals; and the variation of velocity around the circumference of the borehole.

The present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic of an experimental arrangement for measuring shear and compressional velocities in a rock sample as a function of uniaxial stress;

Fig. 2 is a graph of compressional velocities as a function of uniaxial stress for three rock samples;

Fig. 3 is a graph of shear velocities as a function of uniaxial stress for the three rock samples;

Fig. 4 is a graph of the nonlinear parameter  $\partial^2/\partial\sigma$  as a function of uniaxial stress for compressional waves measured in the three rock samples and a fourth rock sample;

Fig. 5 is a graph of the nonlinear parameter  $\partial V^2 / \partial \sigma$  as a function of uniaxial stress for shear waves measured in the four rock samples; and

Fig. 6 is a flow diagram of a preferred method of obtaining in situ a determination of the nonlinear parameter  $\partial V^2 / \partial \sigma$ .

Turning to Fig. 1, an experimental arrangement for measuring compressional and shear velocities as a function of uniaxial stress in a rock sample 21 is seen. The rock sample obtained were cylinders of approximately two inches in diameter, and six inches long. The rock samples were individually placed in a uniaxial press (not shown) which applied pressure parallel to the axis of the rock sample. Acoustic transducer pairs (sources and receivers) 12a, 12b, 14a, 14b, 16a, 16b, and 18a, 18b were mounted on each rock sample so that four different velocities could be measured:  $V_{P1}$  - compressional velocity parallel to the rock axis;  $V_{P2}$  - compressional velocity perpendicular to the rock axis;  $V_{S21}$  - shear velocity perpendicular to the rock axis and polarized parallel to the rock axis; and  $V_{S23}$  - shear velocity perpendicular to the rock axis and polarized perpendicular to the rock axis. Three sandstones (Berea, Portland, Hanson), and one limestone (#1068) were measured. For each rock sample, uniaxial stress was increased by the press in increments until the rock eventually fractured. At each stress increment all four velocities were measured, although the velocities measured perpendicular to the applied stress ( $V_{P2}$  and  $V_{S23}$ ) were of most interest because they are believed to be most relevant to borehole failure caused by external stresses applied perpendicular to the borehole axis.

Results of the tests on the four rock samples with respect to the perpendicularly measured velocities are seen in Figures 2 and 3. Figure 2 shows compressional velocity ( $V_{P2}$ ) versus uniaxial stress in the four samples, while Figure 2 shows shear velocity ( $V_{S23}$ ) versus uniaxial stress in the four samples. A review of Figures 2 and 3 reveals that there is no correlation between rock strength and velocity, as the higher velocity limestone sample failed before a lower velocity Hanson sandstone sample, and the Portland sandstone sample failed before the lower velocity Berea sandstone sample. What is revealed in Figures 2 and 3, however, is that the measured velocities decreased relatively quickly just prior to failure. This decrease is believed to result from dilatancy in the rock sample which is the opening of microcracks caused by increasing non-hydrostatic stresses. Dilatancy has previously been studied in igneous rocks in relation

to earthquake prediction, and was also observed in unconsolidated sand. See Nur, A. "A Note on the Constitutive Law for Dilatancy", *Pageoph*, Vol. 113 (1975).

As set forth in the related cases hereto, the variation in the square of the shear or compressional velocities as a function of stress is a fundamental indication of formation nonlinearity. This may also be derived from an equation for compressional velocity in a hydrostatically stressed isotropic medium set forth by Hughes, D.S. and Kelly, J.L. "Second-Order Elastic Deformation of Solids", *Physical Review* 92, 5; p.1145 (1953):

$$\rho V_p^2 = \lambda + 2\mu - (P/3K)[6l + 4m + 7 + 10\mu] \quad (3)$$

where  $\rho_0$  is the mass density of the formation,  $V_p$  is the compressional wave velocity,  $P$  is the applied pressure,  $\lambda$  and  $\mu$  are the Lamé constants, and  $l$  and  $m$  are third order (nonlinear) elastic constants. From equation (3), it can be seen that the compressional velocity squared, as a function of stress (via hydrostatic pressure  $P$ ) is directly proportional to the nonlinear constants  $l$  and  $m$  (and the linear Lamé constants). Based on equation (3), and recognizing that the nonlinear coefficients  $l$  and  $m$  are typically at least two orders of magnitude greater than the linear coefficients, it will be appreciated that if the velocity does not significantly vary with stress, the rock is considered to be linear. However, if the velocity does significantly vary with stress, the rock can be described as having nonlinear characteristics. Thus, the derivative of the square of the velocity as a function of stress may be considered a direct indication of formation nonlinearity.

Using the data obtained with reference to Figures 2 and 3, values were derived and plotted of the derivative with respect to stress of the square of the velocity ( $dV^2/d\sigma$ ) as a function of stress as seen in Figures 4 and 5. Figure 4 relates to the derivatives of the perpendicular compressional wave velocities, while Figure 5 relates to the derivatives of the shear wave velocities. As seen in Figures 4 and 5, the values of the derivatives drop significantly just prior to rock failure. In fact, it can be seen that a compressional derivative value of between approximately -0.15 and -0.4  $(\text{km/sec})^2/\text{MPa}$ , with a preferred value of -0.2  $(\text{km/sec})^2/\text{MPa}$  can be taken as a defining value of incipient failure as all the rock samples failed within about 10 MPa to 1 MPa after the compressional derivative value dropped below that value range. Likewise, a shear derivative value of approximately -0.075 to -0.2  $(\text{km/sec})^2/\text{MPa}$ , with a preferred value of -0.1  $(\text{km/sec})^2/\text{MPa}$  was likewise a defining indication of incipient failure as all the rock samples failed within about 5 to 0.5 MPa after the shear

derivative value dropped below that value range. It should be appreciated that the defining indications of incipient failure relate to the experimental arrangement of Fig. 1 where there was no overburden pressure. Thus, it is possible that in the formation different values for defining indications of incipient failure will be obtained.

It will also be appreciated that the slope of the derivative curves can be used as an indication of incipient failure as the slopes become large (negative) just prior to rock failure. A preferred negative slope value range defining an indication of incipient failure is between  $-0.02$  to  $-0.07$   $(\text{km/sec})^2/(\text{MPa})^2$ , with a preferred value of  $-0.06$   $(\text{km/sec})^2/(\text{MPa})^2$ , as rocks will typically fail if uniaxially stressed between  $5$  -  $1$   $\text{MPa}$  beyond that point. Again it is noted that these values relate to the experimental arrangement of Fig. 1, and that it is possible that via experimentation in the borehole, other values might be found in formations with overburden pressures.

A preferred manner of determining the derivative of the shear velocity squared with respect to stress  $(\partial V_s^2 / \partial \sigma)$  will be described in relation to Fig. 6 which relates to a borehole tool having a monopole and/or dipole source and acoustic detectors. At 100 the velocity of Stoneley and/or flexural waves, and compressional and shear waves generated by the source(s) are measured. The velocities (including velocity dispersion curves for the Stoneley and flexural waves) are calculated at step 102 by a processor which is either connected to the acoustic detectors in the borehole tool, or is located uphole and coupled to the borehole tool via a wireline. At 104, the borehole pressure at the location of the borehole tool is changed, either by providing the borehole tool with packers which seal off that area of the borehole and a fluid injection means for increasing the pressure in the borehole, or by locating a packer type device on a well head in order to pressurize the entire borehole. Then at 106, at the second pressure, Stoneley and/or flexural waves, and compressional and shear waves are generated and measured again, and at 108, wave velocities at the second pressure are calculated. Using the change in Stoneley and/or flexural wave velocities, as well as the p-wave and s-wave velocities, values for the nonlinear formation parameters  $N_1$  and  $N_2$  are found at step 112. In particular, for each of at least two frequencies (at least one of which is preferably in the 3 kHz to 6 kHz range), a fractional change in the measured acoustic velocity is made at step 112a. From the fractional change, a component generated by the borehole fluid and a component due to linear aspects of the formation are subtracted at step 112b to provide a frequency dependent nonlinear formation

component (B). Then, utilizing an inversion process  $AX = B$  at step 112c according to the following equations (4) - (7), values are obtained for the nonlinear parameters  $N_1$  and  $N_2$ :

$$A = \begin{vmatrix} c_1'^1 c_2'^1 \\ c_1'^2 c_2'^2 \end{vmatrix} \quad (4)$$

$$X = \begin{vmatrix} N_1 \Delta P \\ N_2 \Delta P \end{vmatrix} \quad (5)$$

$$B = \begin{vmatrix} (\Delta V/v)_{\text{Stoneley}} - \Delta V/v_{\text{linear}} - \Delta V/v_{\text{fluid}} \\ (\Delta V/v)_{\text{Stoneley}} - \Delta V/v_{\text{linear}} - \Delta V/v_{\text{fluid}} \end{vmatrix}_{1,2} \quad (6)$$

where  $\Delta V/v_{\text{Stoneley}} = (v_{\text{Stoneley}} - v_{\text{Stoneley}}^{\text{ref}}) v_{\text{Stoneley}}^{\text{ref}}$  (7)

and where  $v_{\text{ref}}^{\text{Stoneley}}$  is the velocity of the Stoneley (or flexural) wave in an unpressurized borehole (or in a borehole at a given reference pressure),  $v^{\text{Stoneley}}$  is the measured velocity of the dispersive Stoneley (or flexural) wave at a known pressure,  $\Delta P$  is the difference in pressure between the reference pressure and the known pressure,  $\Delta V/v_{\text{linear}}$  is the portion of the fractional change in the Stoneley (or flexural) dispersion caused by an increase in the borehole pressure that can be calculated from the linear constants of the formation in the ambient state,  $\Delta V/v_{\text{fluid}}$  is the portion of the fractional change in the Stoneley (or flexural) dispersion caused by an increase in the borehole pressure that can be calculated from the known borehole fluid nonlinearity in the ambient state, and  $c_1$  and  $c_2$  are volume integrals which are a function of frequency and are calculable in terms of the Stoneley (or flexural) wave solution in the ambient state.

With values determined for nonlinear parameters  $N_1$  and  $N_2$ , a determination of a value for the shear derivative  $dV_s^2/d\sigma$  can be made. In particular, where a specimen is in the form of a rod with uniaxial stress applied along the rod axis (i.e., stresses normal to the rod axis are assumed to be zero), a stress derivative of the shear waves propagating normal to the rod axis and polarized normal to the stress direction can be approximated by:

$$\frac{\partial V_{s23}^2}{\partial \sigma} = \frac{(N_2 - N_1) c_{66}}{\rho_0 Y} + \frac{(N_2 - 2) c_{66}}{\rho_0 Y} \quad (8)$$

where  $N_1 = -c_{144}/c_{66}$  and  $N_2 = -c_{155}/c_{66}$ , and  $\nu$  and  $Y$  are respectively Poisson's ratio and Young's modulus in the formation in the reference ambient state. The Poisson's ratio and Young's modulus are a function of the second order constants of the formation and can be expressed by:

$$\nu = \frac{c_{12}}{2(c_{12} + c_{66})} \quad (9)$$

$$Y = \frac{c_{66}(3c_{12} + 2c_{66})}{(c_{12} + c_{66})} \quad (10)$$

On the other hand, if the specimen is long along the propagation direction, a plane strain approximation normal to the propagation direction is an appropriate assumption. In this case, the stress derivative of the shear wave polarized normal to the stress direction is given by:

$$\frac{\partial V_{s23}^2}{\partial \sigma} = N_1 \frac{(\nu^2 - 1)c_{66}}{\rho_0 Y} - (2 - N_2) \frac{\nu(1 + \nu)c_{66}}{\rho_0 Y} \quad (11)$$

Therefore, the stress derivative of  $V_{s23}^2$  can be readily approximated from either equations (8) or (11), and typically, the stress derivatives for a rock sample will fall between these approximations. Thus, at 121 of Fig. 6, the stress derivative of  $V_{s23}^2$  (i.e.,  $\frac{\partial V_{s23}^2}{\partial \sigma}$ ) is calculated according to equations (8) and/or (11). If the stress derivative is calculated in accordance with both sets of equations, the results may be averaged if desired.

As set forth above, once a value for the stress derivative is calculated, a determination can be made as to whether the formation is in danger of incipient failure. For example, as suggested at 131 of Fig. 6, the determined value of the shear derivative can be compared to a desired threshold value such as  $-0.1 \text{ (km/sec)}^2/\text{MPa}$ . If the shear derivative is less than or equal to the desired threshold value, incipient formation failure can be declared; whereas, if the shear derivative is greater than the threshold value, the formation can be declared to be not near failure. Alternatively, or in addition, at 133, the change in the stress derivative as a function of stress can be obtained at the ambient state, and at 135, this value can be compared to another desired threshold value such as  $-0.06 \text{ (km/sec)}^2/\text{MPa}^2$ . If the value of the change in the stress derivative as a function of stress is less than or equal to that threshold value, incipient formation failure can be declared, whereas, if the derivative of the shear

derivative is greater than that threshold value, the formation can be declared to be not near failure. Further yet, if a value for the compressional derivative is obtained, that value can be compared at 137 to yet another desired threshold value such as -0.2  $(\text{km/sec})^2/\text{MPa}$ . Again, if the compressional derivative is less than or equal to the compressional derivative threshold value, incipient formation failure can be declared, whereas if the compressional derivative is greater than the threshold value, the formation can be declared to be not near failure. Likewise, if a derivative with respect to stress of the compressional derivative is obtained, that value can be compared to the same threshold value as the derivative of the shear derivative to determine incipient formation failure.

It will be appreciated that, if desired, other threshold values can be utilized. For example, the threshold shear derivative value is preferably chosen between approximately -0.075 to -0.2  $(\text{km/sec})^2/\text{MPa}$ , while the threshold derivative of the shear (or compressional) derivative value is preferably chosen between -0.02 to -0.07  $(\text{km/sec})^2/(\text{MPa})^2$ . The threshold compressional derivative value is preferably chosen between approximately -0.15 and -0.4  $(\text{km/sec})^2/\text{MPa}$ . However, yet other threshold values can be utilized.

An alternative manner of determining the in situ value of  $\partial^2/\partial\sigma$  is to take velocity measurements of only the shear and/or compressional waves at two different pressures in the borehole (the pressure relating to stress) and to deconvolve the effect the radial and hoop stress components on the change in velocity measurement.

According to other aspects of the invention, the slope of other indications of nonlinearity in the formation with respect to a change in stress (i.e., the derivative with respect to stress) can be used to provide an indication of incipient failure. Such indications of nonlinearity include: the amplitude of a second harmonic tube wave generated in the borehole; the amplitude of an acoustic signal generated in the formation which has a frequency equal to the difference between two acoustic source signals; and the variation of velocity around the circumference of the borehole.

There have been described and illustrated herein methods for predicting mechanical failure in formations. While particular embodiments have been described, it is not intended that the invention be limited thereto, as it is intended that the invention be as

broad in scope as the art will allow and that the specification be read likewise. Thus, while particular preferred stress and compressional derivative threshold values and ranges were provided for determining whether a formation is in incipient failure, it will be appreciated that other thresholds could be utilized. Also, while preferred methods of obtaining in situ values for the derivative with respect to stress of the square of the shear velocity ( $\partial V_s^2 / \partial \sigma$ ) were described, it will be appreciated that other methods could be utilized within the scope of the invention.

## CLAIMS

1. A method of determining whether an underground formation is subject to incipient stress failure, comprising:
  - a) determining a value of a nonlinear parameter of the formation;
  - b) comparing said value with a predetermined threshold value in order to determine whether said formation is subject to incipient stress failure.
2. A method as claimed in claim 1, wherein the value of the nonlinear parameter is determined using an acoustic technique.
3. A method as claimed in claim 1 or 2, wherein the formation surrounds a borehole and the value of the nonlinear parameter of the formation is determined by measurements made by a tool placed in the borehole adjacent the formation of interest.
4. A method as claimed in claim 4, wherein the tool comprises acoustic sources and receivers and determines compressional wave velocities and/or shear wave velocities from which the value of the nonlinear parameter is determined.
5. A method as claimed in any preceding claim, wherein the nonlinear parameter is a derivative of a square of a shear velocity with respect to formation stress  $\partial V_s^2 / \partial \sigma$ .
6. A method as claimed in claim 5, wherein the threshold value is chosen from the range between -0.075 and -0.2  $(\text{km/sec})^2 / \text{MPa}$ .
7. A method as claimed in claim 6, wherein the threshold value is substantially -0.1  $(\text{km/sec})^2 / \text{MPa}$ .
8. A method as claimed in any of claims 1 to 4, wherein the nonlinear parameter is a derivative of a square of a compressional velocity with respect to formation stress  $\partial V_p^2 / \partial \sigma$ .

9. A method as claimed in claim 8, wherein the threshold value is chosen from the range between -0.15 and -0.4  $(\text{km/sec})^2/\text{MPa}$ .
10. A method as claimed in claim 9, wherein the threshold value is substantially - 0.2  $(\text{km/sec})^2/\text{MPa}$ .
11. A method as claimed in claim 5, wherein the nonlinear parameter is the slope of the derivative of a square of a shear velocity with respect to formation stress  $\partial V_s^2 / \partial \sigma$ .
12. A method as claimed in claim 11, wherein the threshold value is chosen from a range between -0.02 to -0.07  $(\text{km/sec})^2/(\text{MPa})^2$ .
13. A method as claimed in claim 12, wherein the threshold value is substantially - 0.06  $(\text{km/sec})^2/(\text{MPa})^2$ .
14. A method as claimed in claim 8, wherein the nonlinear parameter is the slope of the derivative of a square of a compressional velocity with respect to formation stress  $\partial V_p^2 / \partial \sigma$ .
15. A method as claimed in claim 14, wherein the threshold value is chosen from the range between -0.02 to -0.07  $(\text{km/sec})^2/(\text{MPa})^2$ .
16. A method as claimed in claim 15, wherein the threshold value is substantially - 0.06  $(\text{km/sec})^2/(\text{MPa})^2$ .

**Amendments to the claims have been filed as follows**

1. A method of determining whether an underground formation is subject to incipient stress failure, comprising:
  - (a) determining compressional wave velocities and/or shear wave velocities of the formation using an acoustic technique;
  - (b) determining, from the compressional wave velocities and/or shear wave velocities, a value of a nonlinear parameter of the formation which comprises a derivative of a square of a shear velocity with respect to formation stress  $\partial V_s^2 / \partial \sigma$  or a derivative of a square of a compressional velocity with respect to formation stress  $\partial V_p^2 / \partial \sigma$ ;
  - (c) comparing said value with a predetermined threshold value in order to determine whether said formation is subject to incipient stress failure.
2. A method as claimed in claim 1, wherein the formation surrounds a borehole and the value of the nonlinear parameter of the formation is determined by measurements made by a tool placed in the borehole adjacent the formation of interest.
3. A method as claimed in claim 2, wherein the tool comprises acoustic sources and receivers and determines compressional wave velocities and/or shear wave velocities from which the value of the nonlinear parameter is determined.
4. A method as claimed in claim 1, 2 or 3, wherein the value comprises a derivative of a square of a shear velocity with respect to formation stress  $\partial V_s^2 / \partial \sigma$  and the threshold value is chosen from the range between -0.075 and -0.2  $(\text{km/sec})^2 / \text{MPa}$ .
5. A method as claimed in claim 4, wherein the threshold value is substantially -0.1  $(\text{km/sec})^2 / \text{MPa}$ .
6. A method as claimed in claim 1, 2 or 3, wherein the value comprises a derivative of a square of a compressional velocity with respect to formation stress  $\partial V_p^2 / \partial \sigma$  and the threshold value is chosen from the range between -0.15 and -0.4  $(\text{km/sec})^2 / \text{MPa}$ .

7. A method as claimed in claim 6, wherein the threshold value is substantially -0.2  $(\text{km/sec})^2/\text{MPa}$ .
8. A method as claimed in claim 1, 2 or 3, wherein the nonlinear parameter is the slope of the derivative of a square of a shear velocity with respect to formation stress  $\partial V_s^2 / \partial \sigma$ .
9. A method as claimed in claim 8, wherein the threshold value is chosen from a range between -0.02 to -0.07  $(\text{km/sec})^2/(\text{MPa})^2$ .
10. A method as claimed in claim 9, wherein the threshold value is substantially -0.06  $(\text{km/sec})^2/(\text{MPa})^2$ .
11. A method as claimed in claim 1, 2 or 3, wherein the nonlinear parameter is the slope of the derivative of a square of a compressional velocity with respect to formation stress  $\partial V_p^2 / \partial \sigma$ .
12. A method as claimed in claim 11, wherein the threshold value is chosen from the range between -0.02 to -0.07  $(\text{km/sec})^2/(\text{MPa})^2$ .
13. A method as claimed in claim 12, wherein the threshold value is substantially -0.06  $(\text{km/sec})^2/(\text{MPa})^2$ .

15  
**Patents Act 1977**  
**Examiner's report to the Comptroller under Section 17**  
**(The Search report)**

Application number  
**GB 9516618.7**

<b>Relevant Technical Fields</b>	<b>Search Examiner</b> <b>S J DAVIES</b>
(i) UK Cl (Ed.N)      G1G - GEL, GMB	Date of completion of Search
(ii) Int Cl (Ed.6)      G01V - 1/00, 1/48, 1/50	9 NOVEMBER 1995
<b>Databases (see below)</b> (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii)	Documents considered relevant following a search in respect of Claims :- 1-16

**Categories of documents**

X: Document indicating lack of novelty or of inventive step.	P: Document published on or after the declared priority date but before the filing date of the present application.
Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.	E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.
A: Document indicating technological background and/or state of the art.	&: Member of the same patent family: corresponding document.

Category	Identity of document and relevant passages	Relevant to claim(s)
X, E	GB 2288021 A      (SCHLUMBER) see page 7, lines 25-30; page 10, line 29 - page 11, line 22	1-4

**Databases:** The UK Patent Office database comprises classified collections of GB, EP, WO and US patent specifications as outlined periodically in the Official Journal (Patents). The on-line databases considered for search are also listed periodically in the Official Journal (Patents).